An assessment of the accuracy of 14.5 years of Nimbus 7 TOMS Version 7 ozone data by comparison with the Dobson network

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Abstract. A Version 7 algorithm and calibration have been applied to the 14.5 year Nimbus 7 TOMS ozone record (1978- 1993). The ozone retrieval algorithm has been significantly improved for cloudy conditions and for high solar zenith angles, and the radiative transfer used in the algorithm is more accurate. New calibration techniques have been used that produce a very stable data set even after 1990 when TOMS degradation became significant. TOMS ozone now agrees with average ozone from an ensemble of 30 northern hemisphere ground stations (Dobsons and Brewers) to within $\pm 1\%$ throughout most of the 14.5 year record. The time-dependent drift relative to Dobson is 0.29% per decade through the end of the data record. There is almost no solar zenith angle dependence in the comparison for angles below about 80°, but data should be used with caution for larger solar zenith angles. There is also a residual total ozone dependence in the TOMS-Dobson difference, of about 1% per 100 DU.

Introduction

The entire 14.5 year record of total column ozone data from the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) has recently been re-processed using a Version 7 (V7) algorithm and calibration. The ozone data record covers the period from November 1978 until the failure of the TOMS chopper wheel on May 6, 1993. This long record of global ozone data from a single instrument has been a key data set for detecting the decline in ozone since 1979 [*Stolarski et al.*, 1991]. In order to continue to monitor ozone during a crucial period when ozone is predicted to reach a minimum and begin to recover, it will be necessary to create a stable, consistent data record from multiple TOMS and SBUV (Solar Backscatter Ultraviolet) instruments. Many of the techniques needed to maintain both the time-dependent calibration and the absolute instrument-to-instrument calibration have been developed with the V7 algorithm. The purpose of this paper is to validate these techniques by comparing the Nimbus 7 TOMS ozone data with data from the world-wide network of Dobson and Brewer instruments (GO_3OS).

TOMS Version 7

Details of the V7 algorithm and of the calibration applied to the Nimbus 7 TOMS will be given in papers now in preparation; only a brief summary of the most important changes can be given here. Several improvements were made in the ozone retrieval algorithm. Wavelength triplets are now used to derive ozone instead of pairs. The A triplet, for example, consists of the old A pair, 312.5 and 331.2, coupled with 380 nm. Use of a triplet instead of a pair removes the effect of errors that are linear with wavelength, including most of the effect of wavelength-dependent surface reflectivity. The use of triplets to derive ozone is equivalent to doing pair justification [*Herman et al.*, 1991] on a scan-by-scan basis, so this change alone guarantees a very stable data set even if no other calibration is done.

The radiative transfer calculation used to generate the TOMS look-up tables was improved, including a correction for Raman scattering [*Joiner et al.*, 1995]. Two changes improve the ozone retrieval in the presence of clouds. The radiative transfer now treats a partial-cloud scene as a combination of high clouds and surface rather than as a uniform reflecting surface with an average altitude and reflectivity. A second change is that the ISCCP (International Satellite Cloud Climatology Project) cloud climatology as a function of month, latitude, and longitude is used. Previously it was assumed on the basis of THIR (Temperature and Humidity Infrared Radiometer) data that cloud height could be approximated as a simple function of latitude, but we found that significant errors were made in areas of persistent marine stratocumulus [*Thompson et al.*, 1993]. These persistent low clouds are accounted for in the ISCCP climatology. Finally, changes have been made to improve accuracy at high solar zenith angles, including profile shape selection based on B-C triplet differences.

The calibration of the Nimbus 7 TOMS has been improved. Re-analysis of the original pre-launch wavelength calibration records revealed that there had been an error of -0.116 nm in the wavelengths used. This error was responsible for the +4% offset in ozone between TOMS and the world standard Dobson instrument I83 [*McPeters and Komhyr*, 1991]. Pair justification [*Herman et al.*, 1991] was used to maintain the instrument calibration in Version 6 (V6), but after 1990 the instrument's response began to change more rapidly and it was necessary to use a different technique. The ratio of the backscattered radiance to the extraterrestrial solar irradiance is used to derive ozone. In V7 a constant solar flux is used instead of the measured time-dependent solar flux. This eliminates the diffuser as a source of error but introduces internal instrument change as the primary source of error. In this new technique, known as the spectral discrimination technique, instrument calibration is maintained by stabilizing the time dependence of the ratio of two long wavelength (ozone independent) channels. The result was validated internally by comparing with the results of pair justification applied as in V6, and externally by comparing with SBUV in carefully matched fields of view.

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Data Used in the Comparison

The TOMS-Dobson data comparison was done using TOMS overpass data. Nimbus 7 was in a near-noon sun synchronous polar orbit. TOMS measured ozone in a right-to-left scan of 35 individual measurements across the orbital track to give complete inter-orbit coverage. Each day the single TOMS field of view (FOV) most nearly co-located with the ground station's location is selected as the match. Near nadir this FOV is a 50 km square, but at the outermost scan positions the FOV is approximately 125 km by 280 km. At high latitudes a given ground location can be viewed from multiple orbits. In this case a scan with very high optical path is rejected in favor of one with lower optical path in order to improve accuracy.

The Dobson and Brewer data used in the comparison were the data available as of February 1996 from the World Ozone Data Center, Atmospheric Environment Service, Toronto, Canada. The re-evaluation of historical Dobson data initiated by *Bojkov et al.* [1988, 1990] has now been carried out for a number of stations, leading to a significant improvement in the quality of these data records. Re-analyzed data from the US stations [*Komhyr*, private communication] have been used in this comparison, even though these data are still in the process of being submitted to the World Ozone Data Center. All observation codes are used in the comparisons that follow in order to maximize the number of matches. A comparison of TOMS data to direct sun A-D pair (codes 00 for Dobson and 90 for Brewer) data has been done and results are nearly identical to those shown here for most stations [*Labow and McPeters*, 1993].

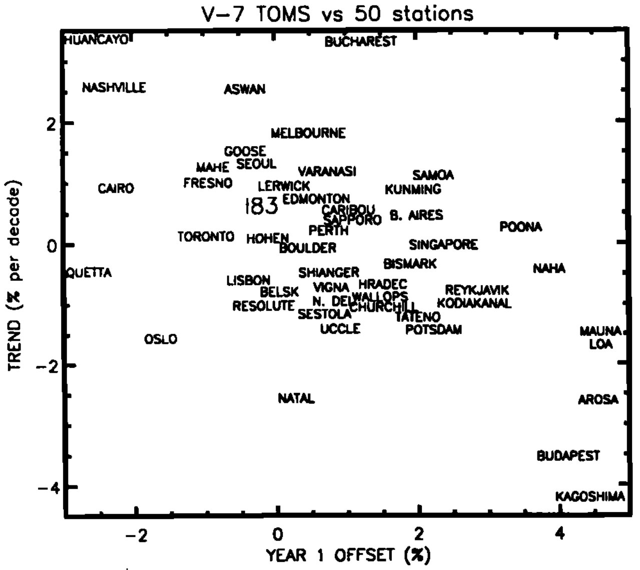

Figure 2. The average bias in 1979 (x axis) between TOMS and individual ground stations, plotted against the average trend between TOMS and each station (y axis).

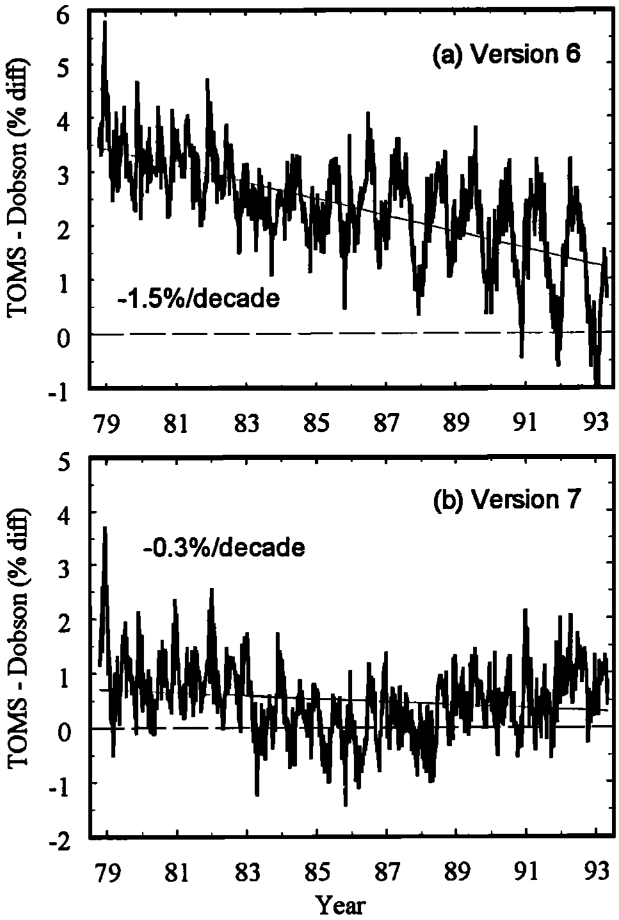

Figure 1. Weekly averages of the percent difference between TOMS ozone and ozone from 30 northern hemisphere (25°N to 55°N) ground stations for (a) Version 6 TOMS data in upper plot, and (b) Version 7 TOMS data in lower plot.

The Comparisons

Figure 1 shows a comparison of TOMS overpass data with data from an average of 30 northern hemisphere mid-latitude (25°N to 55°N) Dobson and Brewer stations. Over 117,000 daily measurements from the ground stations were matched against the TOMS overpass data for the time period November, 1978 to May, 1993. It is useful to examine a single hemisphere because seasonally-dependent errors will cancel if two hemispheres are averaged together, giving a false impression of the quality of the data. Problems from very high solar zenith angles (high latitude stations) will be examined separately. Weekly averages of the percent difference (TOMS-Dobson)/TOMS are plotted. The comparison using V6 data is shown at the top (1a), while the V7 comparison is shown at the bottom (1b). From a simple linear fit to the differences there was a clear drift of V6 TOMS relative to Dobson of -1.54% per decade ±0.13% per decade 2σ error. With V7 the drift is reduced to -0.29% ±0.11% per decade. In V6 a seasonally-dependent error developed after 1986, caused in part by profile shape-dependent errors that became larger as the Nimbus 7 orbit drifted to earlier equator crossing times in the later years. This seasonal dependence is largely eliminated in V7. There are apparent shifts remaining in the V7 TOMS-Dobson difference (of about -1% in early 1983 for example) that we cannot explain.

The V7 comparison with 30 northern hemisphere stations is very stable, but the comparison with individual stations can be quite variable. This is illustrated by Figure 2 in which, for each of 50 individual stations, we plot the TOMS-Dobson 1979 average bias on the x axis, and the relative trend (1979-1993) on the y axis. For stations that became operational after 1979, we used the first year's average bias. The figure shows that, for stations worldwide, the bias ranges from +5% to -3%, and the relative trend varies from +3% per decade to -4% per decade. Included in Figure 2 is a point labeled I83, a comparison with the world primary standard

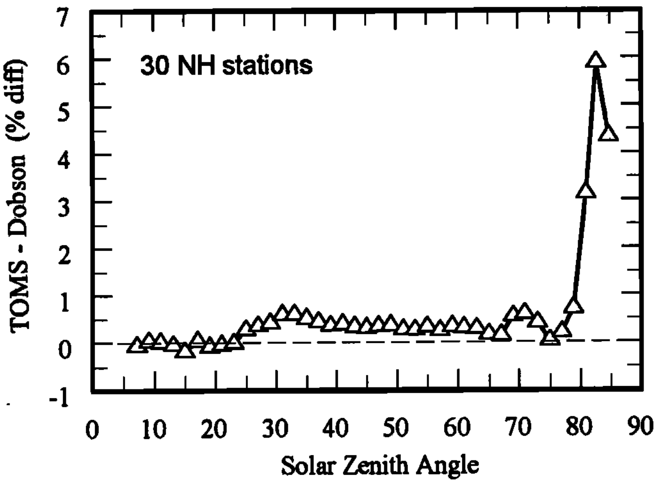

Figure 3. The average difference between TOMS and 30 northern hemisphere ground stations as a function of solar zenith angle.

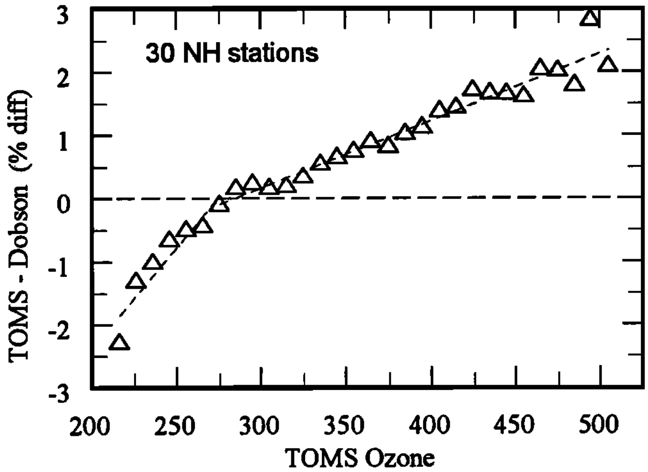

Figure 5. The average difference between TOMS and 30 northern hemisphere ground stations as a function of TOMS total ozone.

Dobson spectrometer number 83. When V6 TOMS data were compared with I83 measurements made at Mauna Loa [*McPeters and Komhyr*, 1991], there was a +4.4% relative bias, but almost no trend. When the same comparison is done using V7 data, the bias drops to 0.03%, again with almost no trend. When similar comparisons are done for measurements made with the same instrument in Boulder, the V6 bias is +2.6% and the relative trend is -0.7% per decade, while the V7 bias is +1.6% and the relative trend is again near zero.

Figure 3 shows the solar zenith angle (SZA) dependence for the comparison with the same set of 30 mid-latitude stations. It shows that the dependence is minimal below about 80° SZA but becomes large thereafter. Figure 4 is a similar plot for 6 individual high latitude (above 60°N) stations. It emphasizes the large station-to-station differences at high SZA, especially for angles above 80°, but it is also true that TOMS errors can become large at high angles. For example, there is a disagreement that we cannot explain between the B triplet (317.5, 331.2, 380 nm) ozone and C triplet (331.2, 339.8, 380 nm) ozone at high latitudes in summer. Fortunately, the B and C triplets agree in winter when the optical path lengths are large and C triplet is actually used. We recommend that TOMS data taken at solar zenith angles greater than 80° be used with caution and that data for angles greater than 84° not be used at all.

Ozone-Reflectivity Dependence

Figure 5 shows a comparison of TOMS and ground station ozone data as a function of TOMS total ozone (in 10 DU bins). Each point represents an average of at least 5 different stations and at least 100 individual daily matchups. The comparison shows a marked increase in the TOMS-Dobson difference as ozone increases.

We identify two distinct regimes: above 275 DU the TOMS-Dobson differences increases by about 1% per 100 DU, while below 275 DU the slope is 2.4% per 100 DU. The increased slope below 275 DU is mostly caused by use of improper climatological profiles in the TOMS algorithm. The 125 DU and 175 DU standard profiles are based on balloonsonde measurements in the Antarctic ozone hole, and have distinctly different tropospheric ozone amounts than normal profiles. For all other profiles the tropospheric component is held constant, since there is no strong support

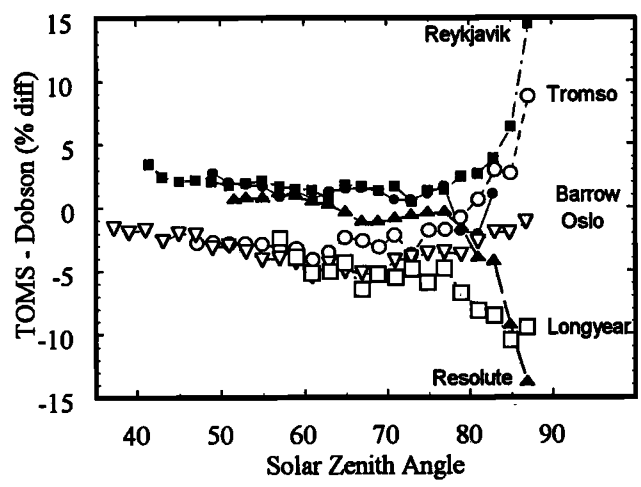

Figure 4. The average difference as a function of solar zenith angle for six individual high latitude (>60°N) stations, showing the high station-to-station variance.

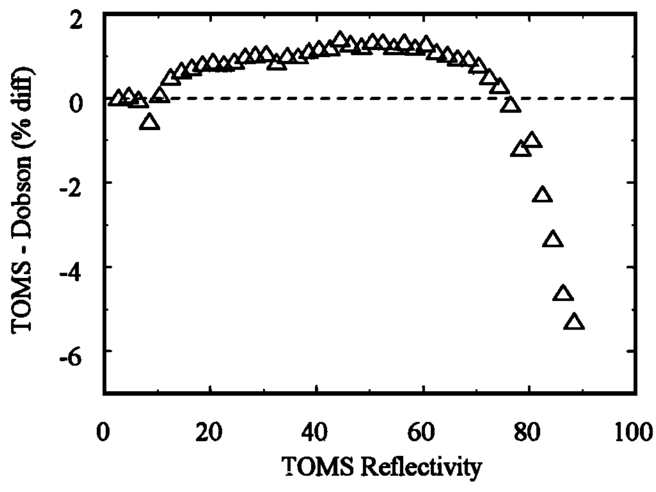

Figure 6. The average difference between TOMS and 30 northern hemisphere ground stations as a function of TOMS reflectivity.

for tropospheric ozone variation with total column ozone. The 225 DU standard profile is a transition profile that contains a lesser amount of tropospheric ozone. In the northern hemisphere when ozone drops below 275 DU, the 225 DU profile with its incorrect tropospheric ozone begins to be used, causing the increasing TOMS-Dobson difference. This is a TOMS algorithm error that could be corrected by a northern-hemisphere-specific ozone climatology.

The reason for the ozone dependence above 275 DU is not as clear. One possibility is that we over-corrected the pre-launch wavelengths discussed earlier, resulting in slightly incorrect ozone cross sections. It is also possible that part of the difference comes from the ground observations. *Basher* [1982] identifies two important errors that might be relevant: stray heterochromatic light from internal scattering within the instrument, and uncertainty in the spectral transmittance of the Dobson instrument's wavelength bands. Stray light can cause an underestimation of ozone by the Dobson instrument due to lower signal-to-noise ratio for the lowest Dobson wavelengths (305.5 & 308.8 nm). Stray light models have shown that, with the presence of stray light in the system, the Dobson instrument will derive lower column ozone values as the airmass increases. *Komhyr* (private communication) estimates that this error could produce as much as half (1%) of the TOMS-Dobson ozone dependence shown in Figure 5.

Because of the geophysical correlation of high ozone with high reflectivity, this total ozone dependence can alias into a reflectivity dependence. The correlation can be explained by the fact that low pressure weather systems tend to be associated with cloudy conditions (higher reflectivity) and also are associated with a lower tropopause and higher total column ozone. The comparison of the TOMS and ground station data as a function of TOMS reflectivity is shown in Figure 6. Up to about 70% reflectivity there is a small slope that is generated by the total ozone dependence, but at very high reflectivities other errors can cause even larger discrepancies. TOMS cannot observe ozone below the cloud level and must extrapolate the total ozone value by accessing a table of standard ozone profiles which were compiled from years of ozonesonde data, so part of the high reflectivity difference may be a TOMS limitation. Part of the error may also be caused by the ground observation. Since the ground stations are also likely to be under cloudy conditions, observations other than the standard direct sun A-D pair may be used. Observations can be made on zenith cloud or possibly delayed until the weather system has passed. Either choice yields a less reliable ozone value [*Komhyr*, 1980, *Basher*, 1982].

Conclusion

The V7 TOMS ozone data incorporate a number of improvements that should enable researchers to more accurately identify geophysical effects associated with total column ozone. Careful comparison of the V7 ozone data from Nimbus 7 TOMS shows that the new data agree well with an average of 30 northern hemisphere Dobson/Brewer stations. In earlier versions of TOMS data, TOMS was 3-4% higher than most ground stations. In V7 the correction of a pre-launch wavelength calibration error brings the absolute agreement with Dobson to within a percent, with TOMS still being higher. The drift between TOMS and Dobson is now near zero (-0.29% $\pm$0.11% per decade), but it might be more accurate to say that they agree to within about a percent. The TOMS-Dobson agreement is good and very independent of solar zenith angle up to about 80° but at higher angles errors become significant. We recommend that TOMS data taken at solar zenith angles greater than 80° be used with caution and that data for angles greater than 84° not be used at all.

We find that the difference between TOMS and Dobson increases with total ozone amount, by about 1% difference per 100 DU of total ozone. This difference is likely a combination of TOMS and Dobson errors. For trend analysis this error should not be a problem since it is not time dependent, but the error can alias into reflectivity dependence since high ozone tends to be associated with high reflectivity conditions.

New information about TOMS ozone from Nimbus 7 and Meteor 3, and from the recently launched Earth Probe and ADEOS TOMS instruments will be posted to the TOMS homepage at: http://jwocky.gsfc.nasa.gov

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References

Basher, R.E., Review of the Dobson Spectrophotometer and its Accuracy, WMO *Global Ozone Research and Monitoring Project Report No. 13*, 1982.

Bojkov, R.D., L. Bishop, W.J. Hill, G.C. Reinsel, and G.C. Tiao, A statistical trend analysis of revised Dobson total ozone data over the northern hemisphere, *J. Geophys. Res.*, *95*, 9785-9807, 1990.

Bojkov, R.D., C.L. Mateer, and A.L. Hansson, Comparison of ground-based and total ozone mapping spectrometer measurements used in assessing the performance of the global ozone observing system, *J. Geophys. Res.*, *93*, 9525-9533, 1988.

Herman, J. R., R. Hudson, R. McPeters, R. Stolarski, Z. Ahmad, S. Taylor, and C. Wellemeyer, A Method for Self Calibration of TOMS to Measure Long Term Global Ozone Change, *J. Geophys. Res.*, *96*, 7531-7546, 1991.

Joiner, J., P.K. Bhartia, R. Cebula, E. Hilsenrath, and R. McPeters, Rotational-Raman Scattering (Ring Effect) in Satellite Backscatter Ultraviolet Measurements, *Applied Optics*, *34*, 4513-4525, 1995.

Komhyr, W.D., Operations Handbook - Ozone Observations with a Dobson Spectrophotometer, *WMO Global Ozone Research and Monitoring Project Report No. 5*, June 1980

Labow, G. and R. McPeters, in Ozone Data for the World: May-June 1993, Vol. 34 No. 3, Atmospheric Environment Service, Downsview-Ontario, Canada

McPeters, R.D. and W.D. Komhyr, Long-term Changes in SBUV/TOMS Relative to World Primary Standard Dobson Spectrometer 83, *J. Geophys. Res.*, *96*, 2987-2994, 1991.

McPeters, R.D., P.K. Bhartia, A.J. Krueger, J.R. Herman, B. Schlesinger, C.G. Wellemeyer, C.J. Seftor, G. Jaross, S.L. Taylor, T. Swissler, O. Torres, G. Labow, W. Byerly, and R.P. Cebula, Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) Data Products User's Guide, NASA Reference Publication 1384, April, 1996.

Stolarski, R.S., P. Bloomfield, R.D. McPeters, and J.R. Herman, Total ozone trends deduced from Nimbus 7 TOMS data, *Geophys. Res. Lett.*, *18*, 1015-1018, 1991.

Thompson, A.M., D.P. McNamara, K.E. Pickering, and R.D. McPeters, Effect of Marine Stratocumulus on TOMS Ozone, *J. Geophys. Res.*, *98*, 23051-23057, 1993.

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